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MEMS Based Pumped Liquid Cooling Systems for Micro/Nano Spacecraft Thermal Control

Gaj Birur and Partha Shakkottai

Jet Propulsion Laboratory

California Institute of Technology, Pasadena, CA

and

Tricia Waniewski Sur

Science Applications International Corp., San Diego, CA

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MEMS pumped liquid cooling system

- Objective
  - to develop MEMS based pumped liquid cooling system for removing over 20 W/cm^2 from high power density microelectronics and science payloads considered for future micro/nano sciencecraft.
- Team
  - JPL: G. Birur, P. Shakottai, A. Green, S. Haapanen, & S. Vargo
  - SAIC: T. Sur
  - Stanford University: T. Kenny and J. Santiago
  - NASA GSFC: T. Swanson
- Sponsor
  - NASA Cross Enterprise Technology Development Program
- Users
  - Code S: Missions to Mars & other planets, SEC missions
  - Code Y: Advanced sensors, high power density payload

Outline

- Background on μspacecraft thermal control
- MEMS based μcooling
- Microchannel heat sink fabrication
- Microcooling numerical and experimental results
- Conclusions and future work

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μspacecraft thermal control

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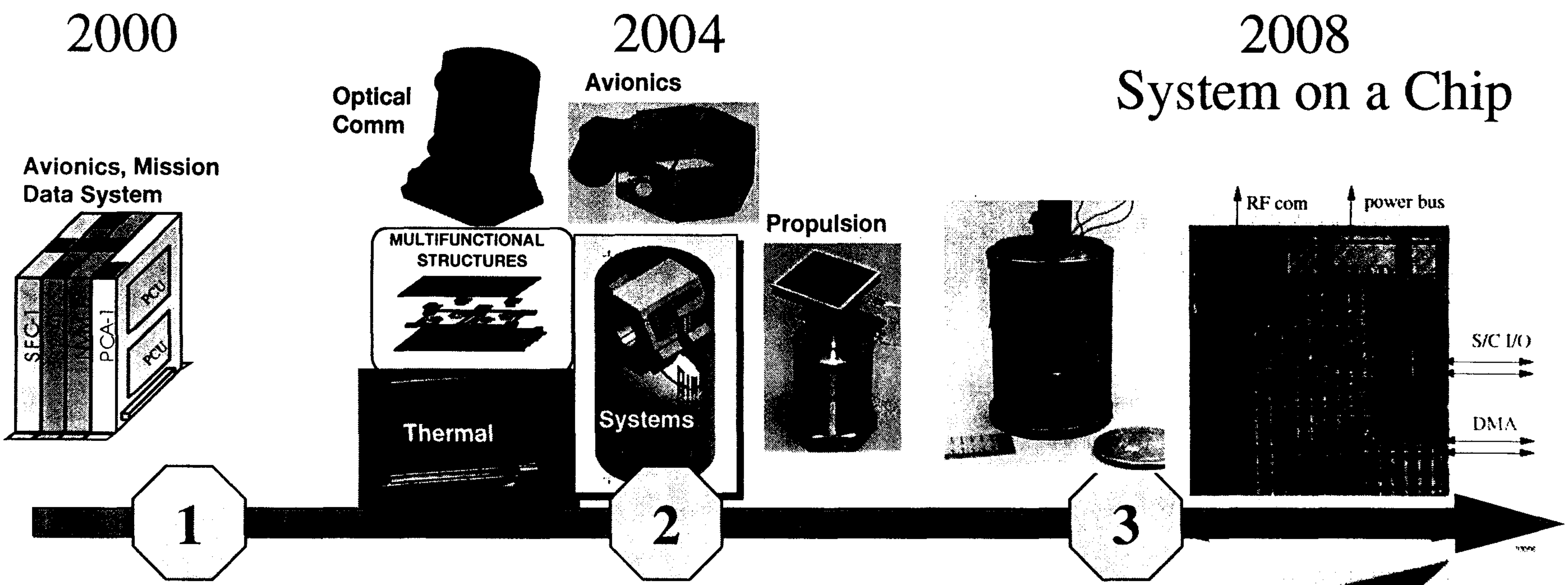
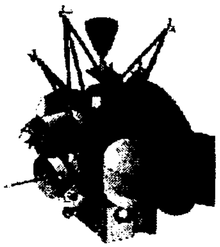
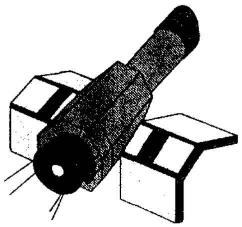
- Thermal control challenges in future μspacecraft
  - Increasing power densities of avionics and science payloads
  - Integrating avionics thermal control with the rest of the spacecraft
  - Increasing multifunctional nature of the spacecraft
- Current state of the art
  - High thermal conductivity materials
  - Miniature and micro heat pipes
  - Thermoelectric coolers

Overview of future space missions

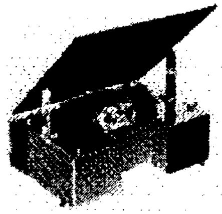




03-05 User Launches:
- Europa Orbiter
- Solar Probe
- Discovery



05-09 User Launches:
- CNSR
- Europa Lander
- Titan Organic Explorer
- Venus Sample Return
- Neptune Orbiter
- Saturn Ring Observer

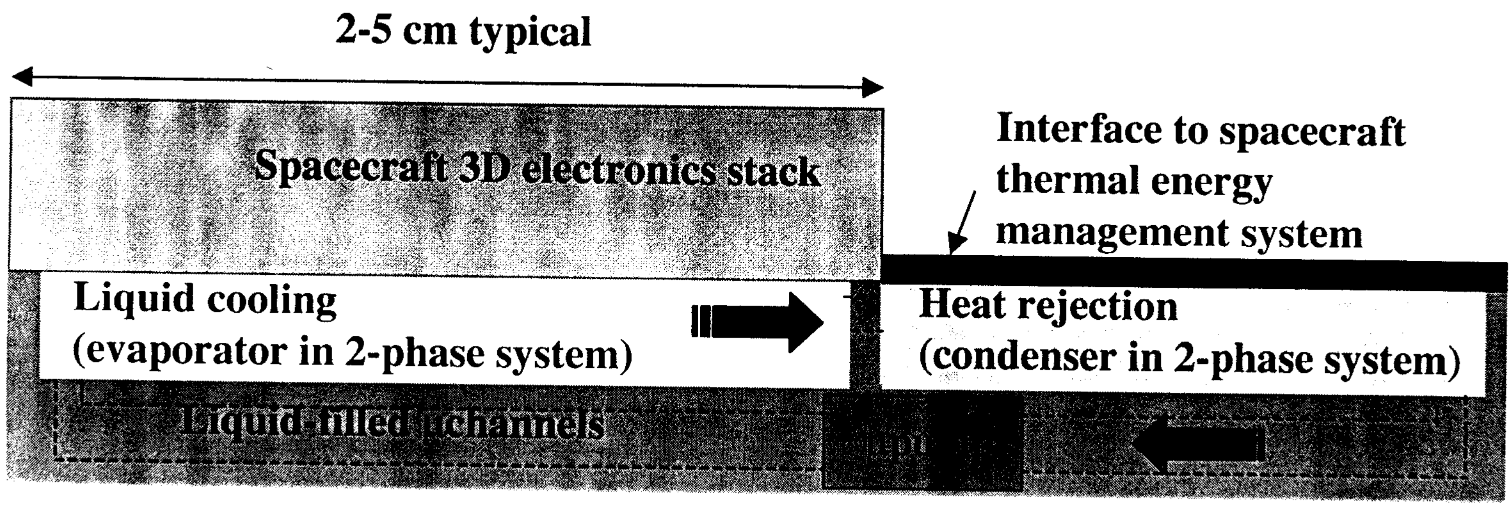


09-12 User Launches:
- Micro and Nano-spacecraft
- Terrestrial Planet Finder

Future space science missions at JPL

- **Mars missions**
  - **Landers, rovers, in-situ production experiments, and robotic support for human colonization missions**
  - **MER (2003), Mars Orbiter (2005), Mars Mega Lander (2007), Mars μmission**
- Missions to comets/asteroids
  - **Comet Nucleus Sample Return Mission**
  - **Asteroid exploration and sample return**
- Missions to other planets
  - **Europa orbiter/lander**
  - **Pluto/Kuiper Express (2008)**
  - **Saturn Ring Observer, Neptune orbiter**
- Other missions
  - **Earth orbiting spacecraft/science payload**
  - **space telescopes, instruments**

MEMS pumped liquid cooling system concept



Advanced MEMS based thermal technologies needed:

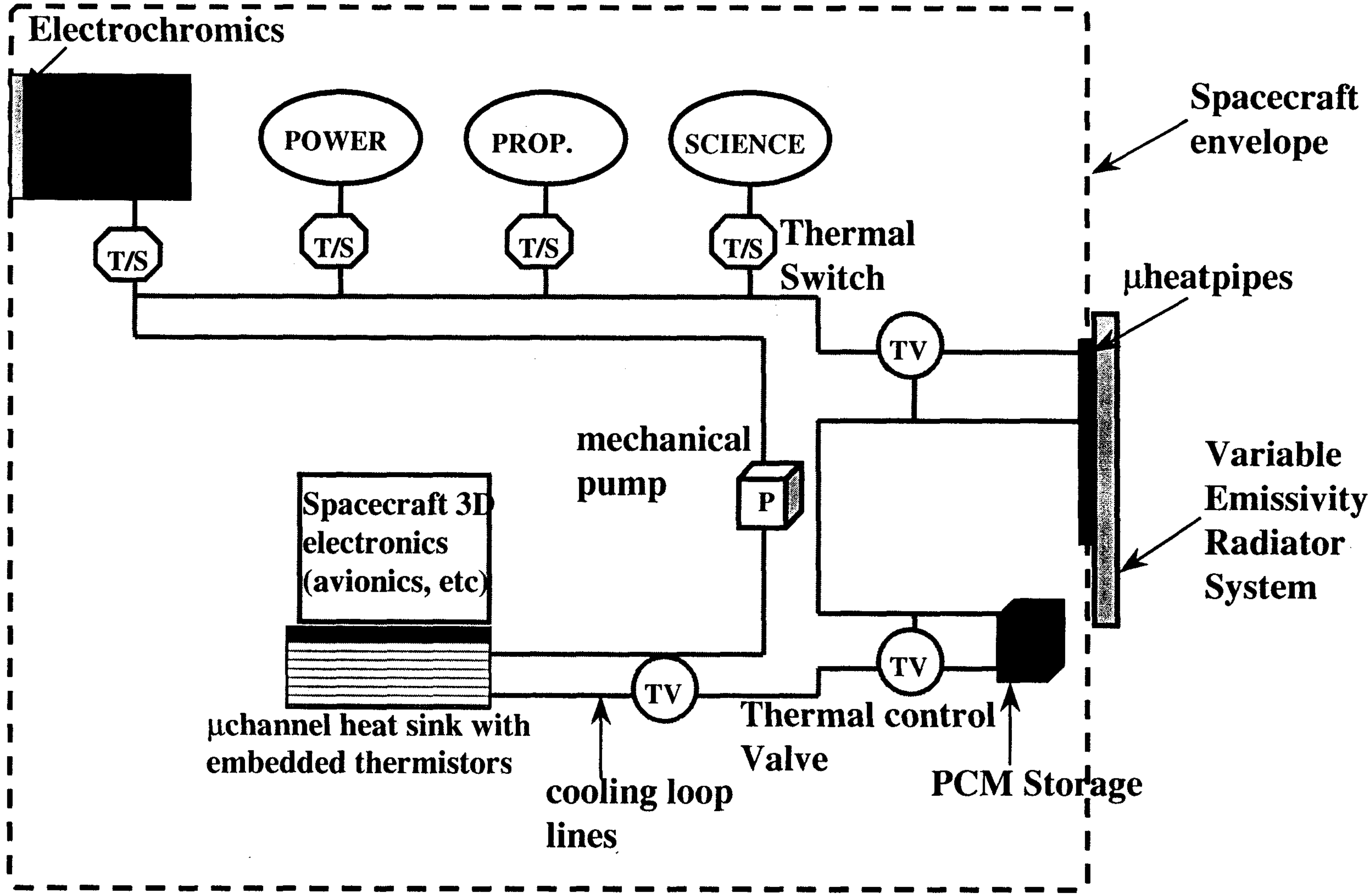
- Microchannels
- Micropumps
- Integrated mcooling system (μvalves, connectors, etc.)

Adv-tech\Papers\Nanospace~\MEMS based~.ppt
March 15, 2001; GB

JPL Advantages of MEMS pumped cooling system

- Increased effectiveness by integration of cooling system with payload.
- Increased freedom in locating electronics or science payload.
- Precision temperature control of payloads by controlling mpump flow rate.
- Ability to function in adverse gravity.
- Removal of large heat fluxes over large distances.
- Expected savings in mass and volume of over 25%.
- Expected temperature reduction of over 20%.

Integrated Thermal Energy Management (ITEM) systems for future μspacecraft



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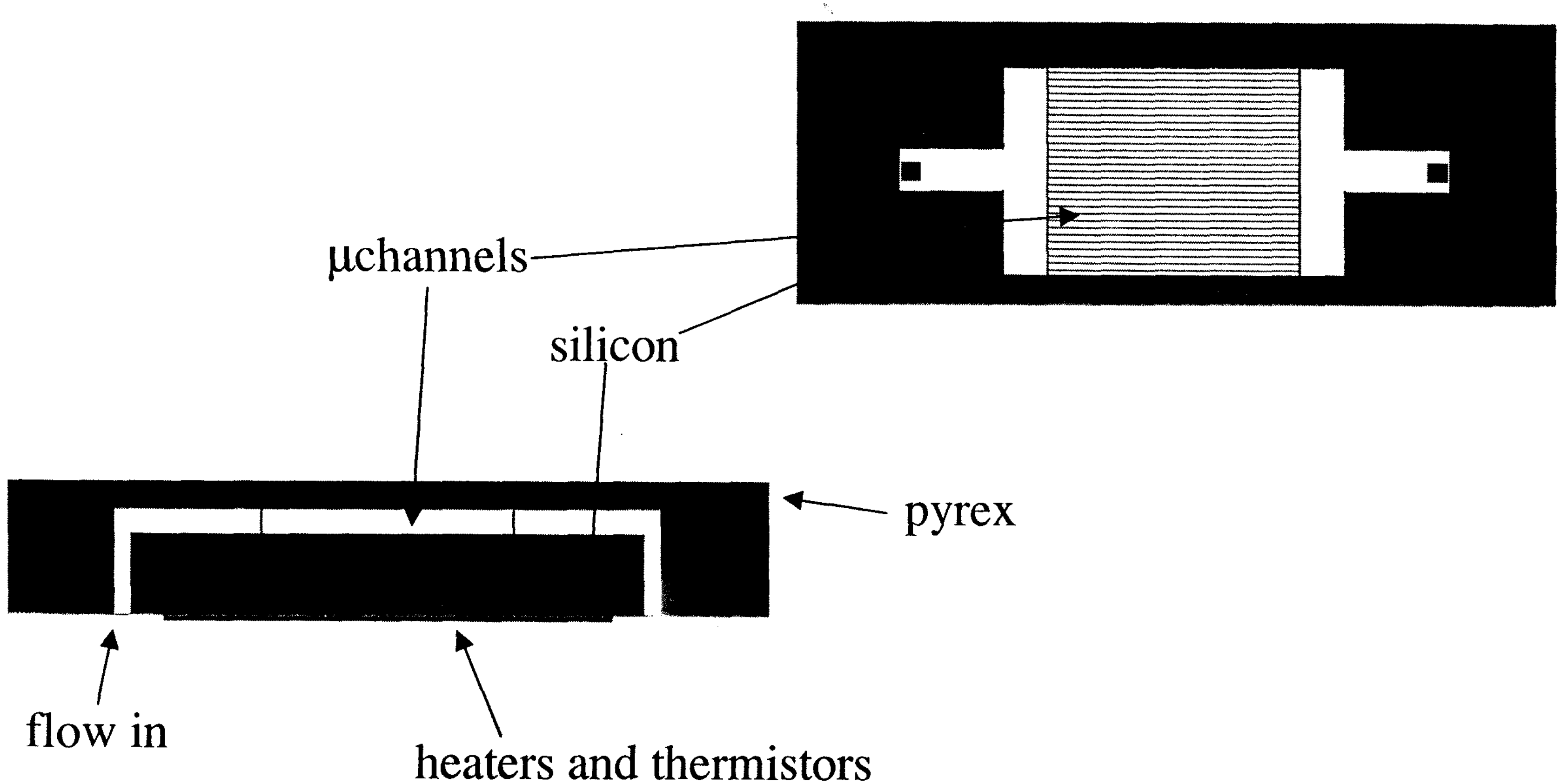
Microchannel Heat Sink



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Design parameters

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- Heater power (q), area (A_h), distance from μchannels (h_2)
- Microchannel configuration
  - Geometry: width (w_c), depth (h_1), spacing (w_w), number
  - Fin efficiency (η)
- Working fluid
  - c_p, ρ, ν, μ
- Volumetric flow rate (Q)

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Fluid performance metrics

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- Total pressure drop
  - Minimize
  - Micropump must be able to provide sufficient pressure to drive fluid through μchannels
- Outlet fluid phase state
  - Liquid, no boiling allowed
  - Eliminates risk of μchannel dry out and μpump damage from uncondensed vapor bubbles

Thermal performance metric

- Minimize thermal resistance to improve heat sink performance

Resistance	Description	Calculation	Typical (°C/W)
R_{cond}	Conduction from the heater through the heat sink interface	L/kA	0.0068
R_{conv}	Convection from heat sink to the cooling fluid	$1/h_cA_c$	>0.024
R_{heat}	Caloric heating of the cooling fluid	$1/mc_p$	0.024
R_{total}			0.1

Heat sinks, single phase water

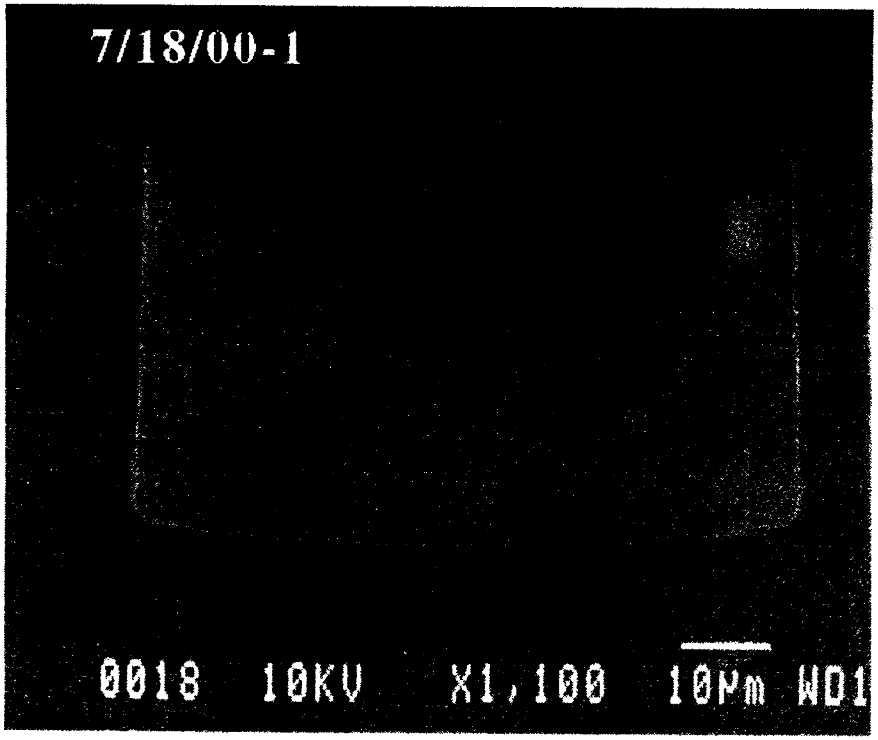
adapted from Harms *et al.* (1997)

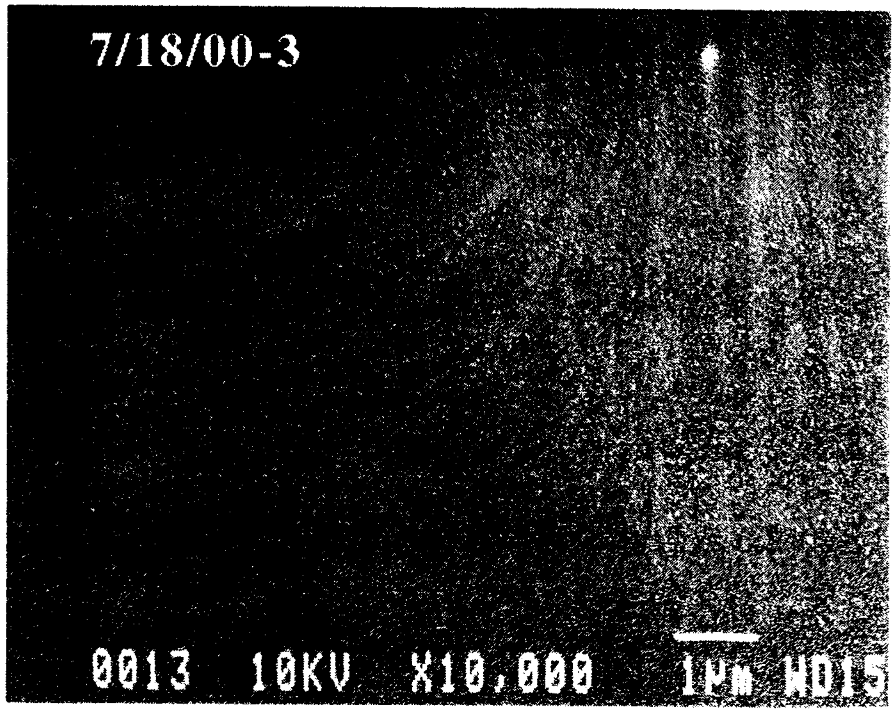
Investigators	Substrate	A_h (A_c) cm^2	l_c cm	h_1 μm	w_c (w_w) μm	q W	Q cc/s	R_{total} °C/W	ΔP kPa
Tuckerman (1984)	Si	1.0 (2.8)	1.40	302	50 (50)	790	8.6	0.090	214
Mahalingam (1985)	Si	14.44 (25)	5.0	1700	200 (100)	1050	63	0.018	-
Kishimoto & Ohsaki (1986)	Alumina	16.0 (62)	8.6	400	800 (1740)	380	13.3	0.132	-
Sasaki & Kishimoto (1986)	Si	2.56 (4.8)	2.4	900	340 (340)	416	-	0.120	20
Riddle *et al.* (1991)	Si	1.0 (3.0)	1.5	320	51 (53)	2500	18.0	0.082	500
Cuta *et al.* (1995)	Cu	4.06 (4.06)	2.05	1000	270 (270)	402.5	3.49	0.168	20.7
Harms *et al.* (1997)	Si	6.25 (6.25)	2.5	1030	251 (119)	415	46.3	0.041	30.5

μchannel Heat Sink Fabrication Summary

- Begin with 4 inch dia., 500 mm thick Silicon wafers.
- Implant heaters and thermistors on back side (Core Systems, Inc.) and anneal.
- Deposit aluminum tracks and pads to make electrical connections on back side.
- Etch the mchannels and holes on front side using DRIE.
- Anodically bond Pyrex7740 glass wafer to front side.
- Dice wafer into three heat sink devices.
- Epoxy surfboard to Si connect to Al pads with wire bonds.

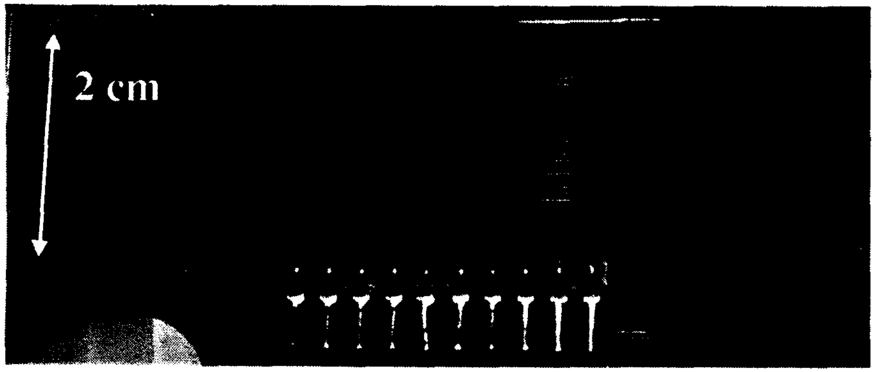
DRIE μchannels



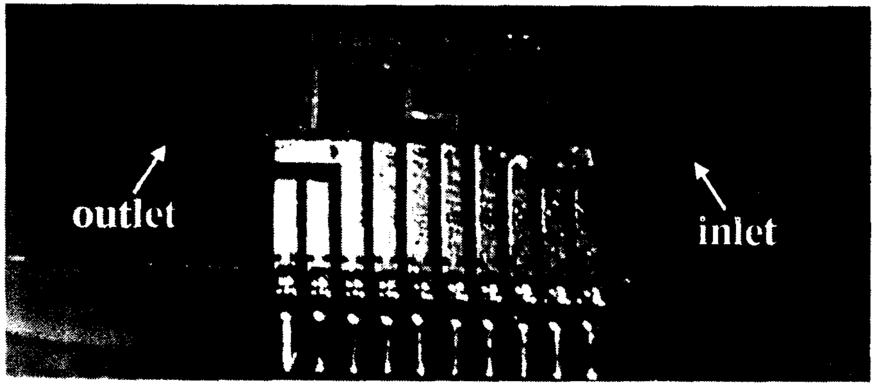


Note rectangular μchannel shape and smooth walls

µchannel heat sink device



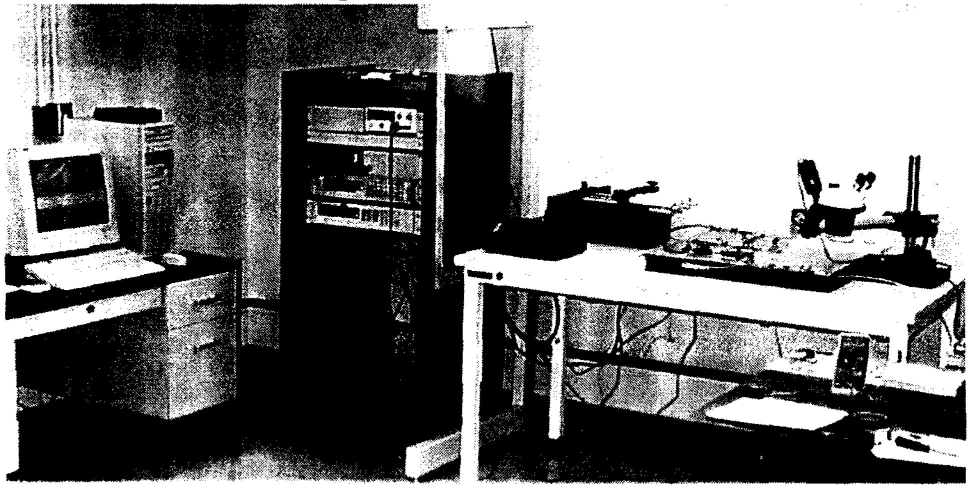
Front side:
- Inlet and outlet manifold and 20 µchannels etched in Si
- Pyrex 7740 glass is bonded to the Si & seals the µchannels



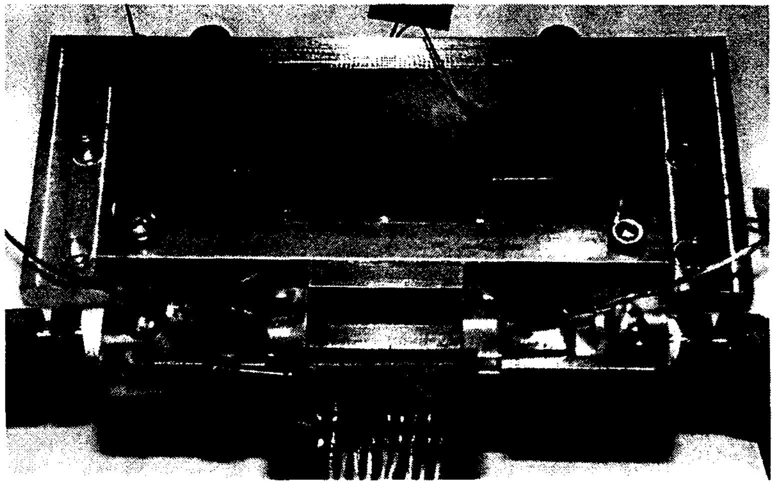
Back side:
- Fluid inlet and outlet holes (4 cm apart)
- Aluminum tracks & pads for electrical connections to implanted heater strips (20) and thermistors (4)
- Wire-bonded surfboard with 10 standard single in-line pins

MEMS pumped liquid cooling system tests

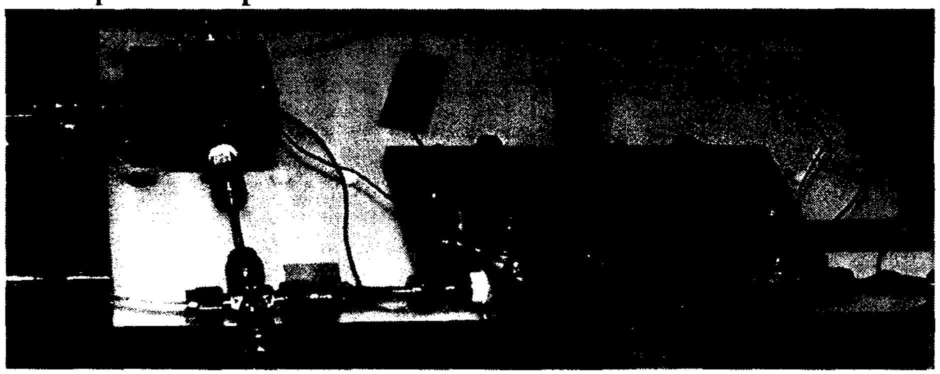
μcooling lab in JPL B18-101



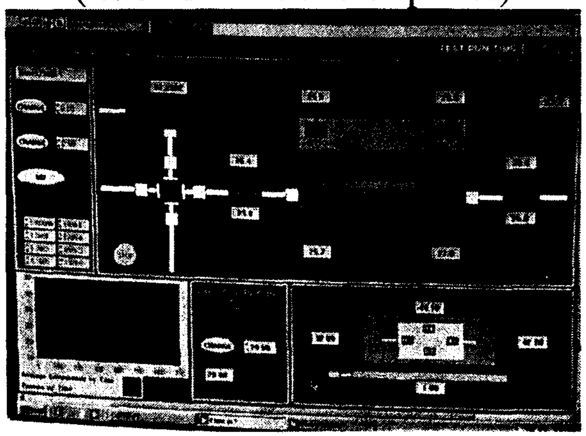
μchannel device, ZIF socket, T/Cs, test fixture



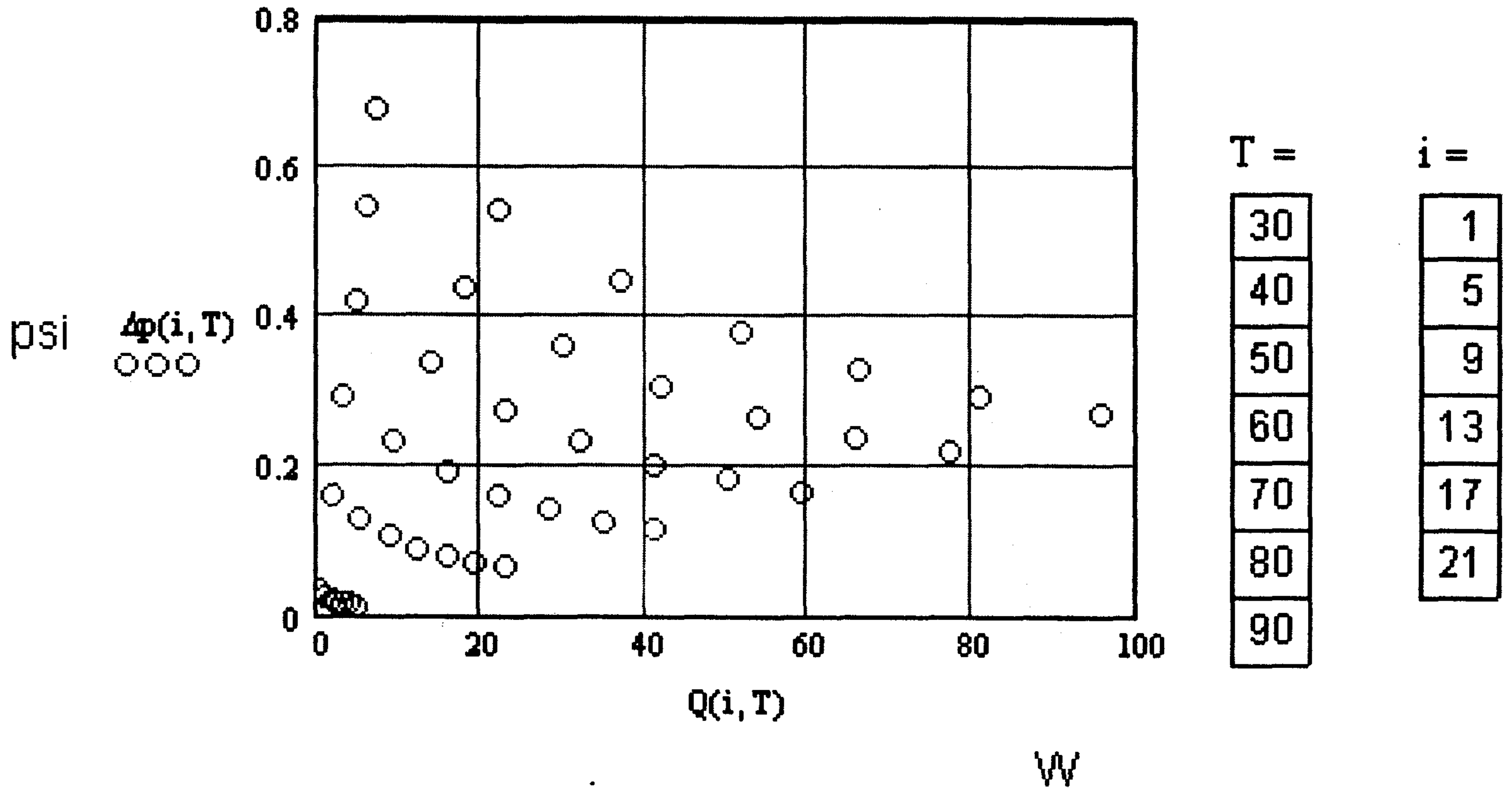
upstream pressure transducer & test fixture



Data acquisition software
(LabVIEW control panel)

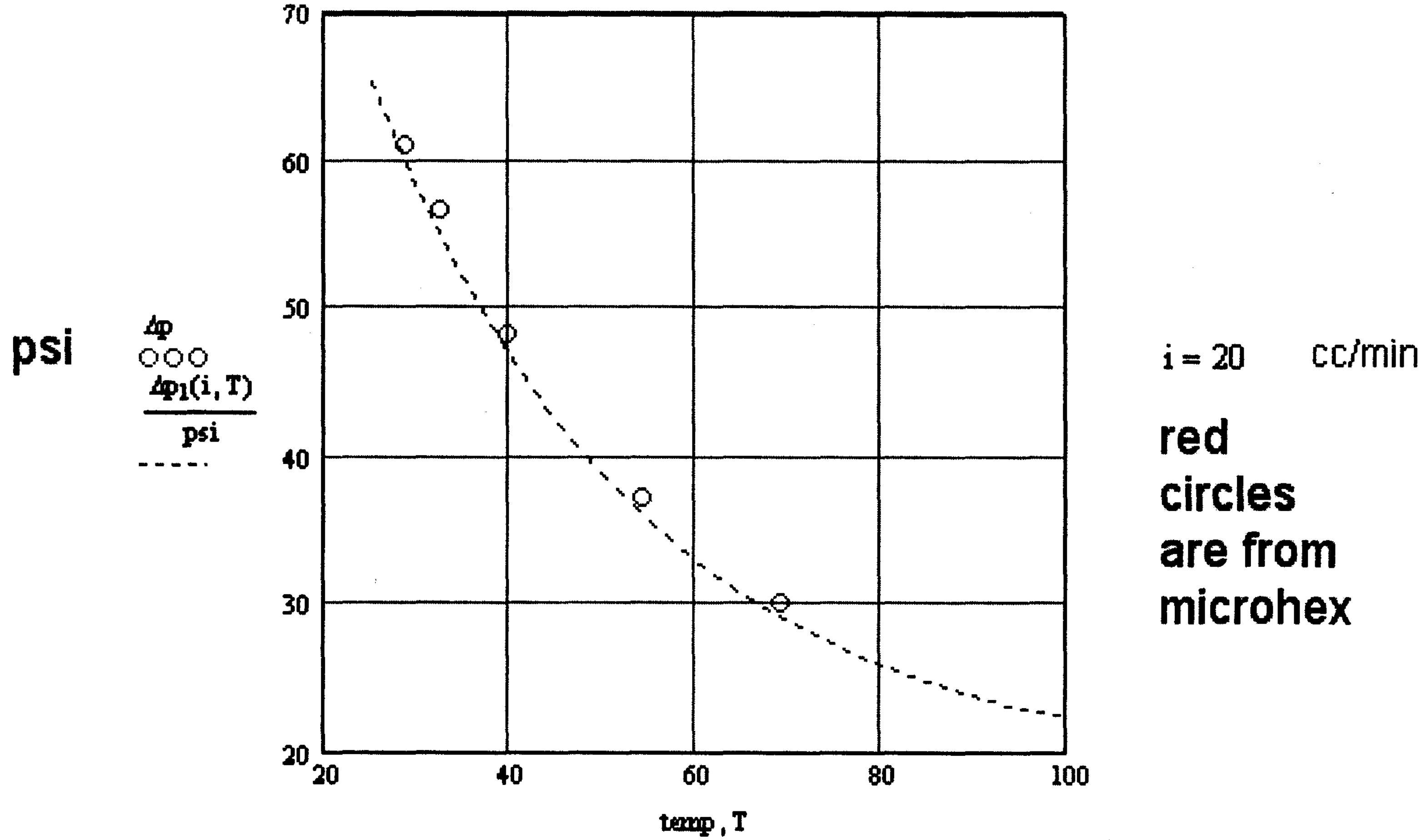


Pressure Drop vs. Heat transfer at various Flow Rates (cc/min) and Temperatures (C)



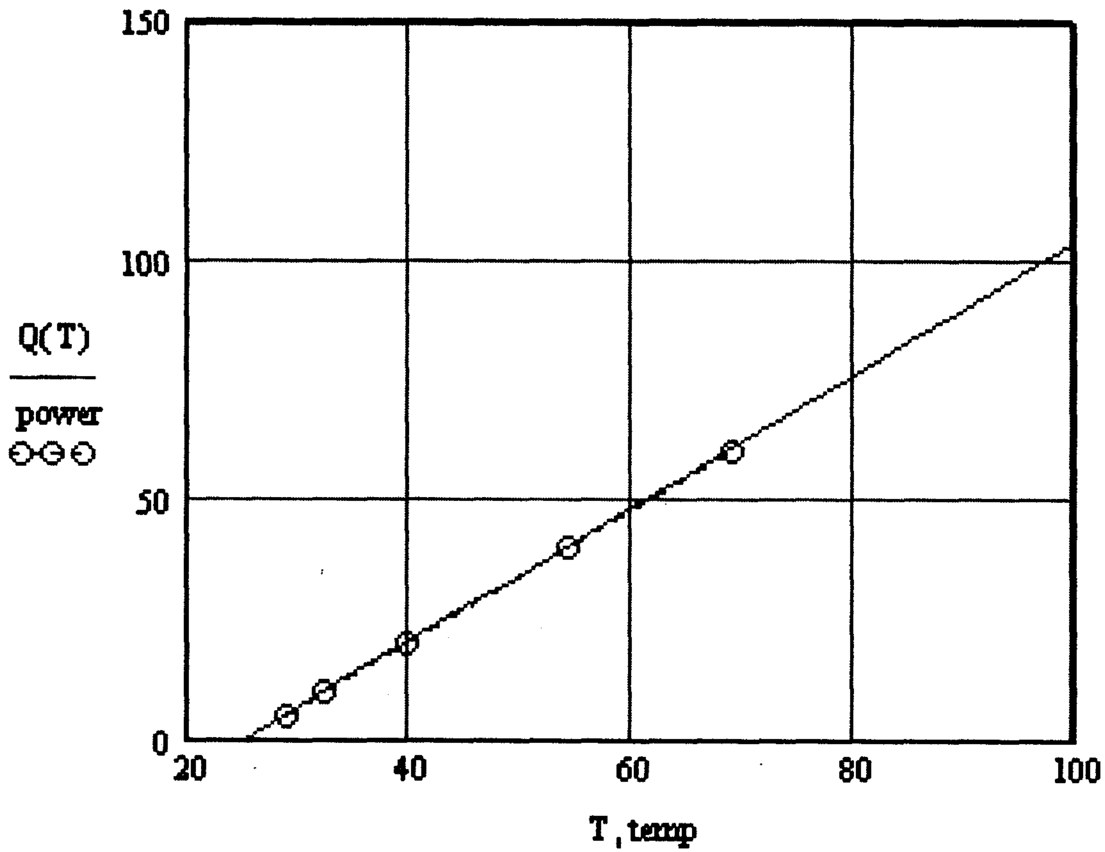
Comparison of Microhex and Mathcad Analyses

Pressure drop vs. temperature



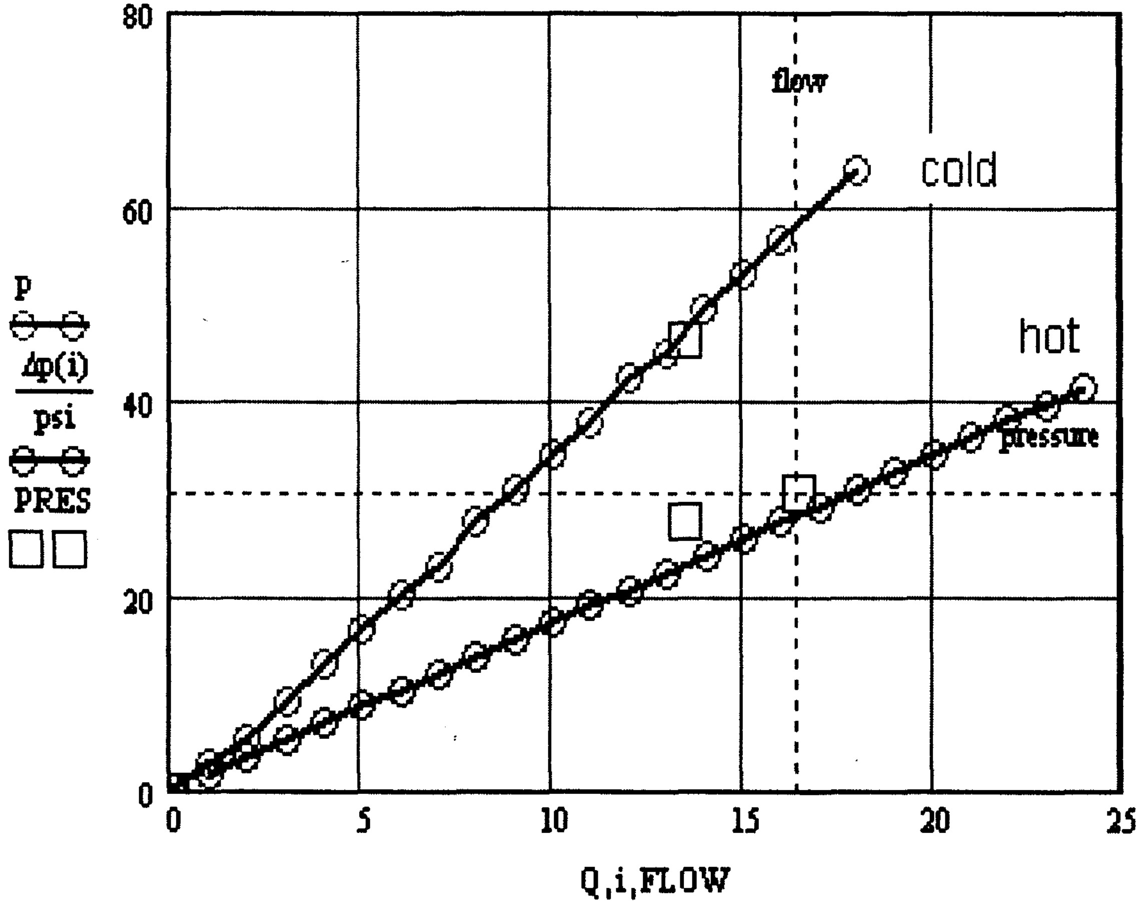
Power vs. temperature

Flow fixed at 20 cc/min



Blue circles are from microhex.

Comparison with data



flow = 16.5 cc/min

pressure = 30.97 psi

2 data points when hot

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Conclusions

- MEMS based pumped liquid cooling system is a promising technique for removing heat from high power density avionics in future µsciencecraft.

- Experimental data from silicon µchannel heat sinks shows that over 25 W/cm^2 can be removed.

- Thermal and hydraulic models were validated using the experimental data and will be used designing optimum channels

Future Work

- Evaluate and test μpumps suitable for the current application.
- Use our validated models to optimize the next generation μchannel geometry. Fabricate and test new devices.
- Evaluate an integrated system consisting of μpump with μchannels.
- Evaluate integrating μcooling system with μspacecraft electronics.